Human-Robot Teaming:

From space robotics to self-driving cars

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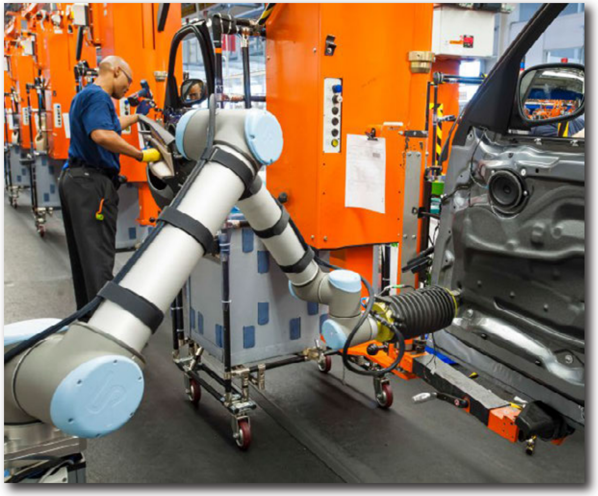
Human-robot teams…



What is a team?

Teams are interdependent

- Members share a common goal
- Group needs > individual need
- Common ground & trust

Norms

- Background (experience, training, knowledge, etc.)
- Organizational structure
- Work protocol (taskwork)

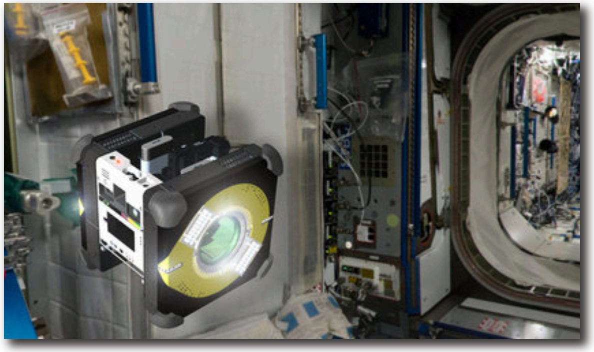
Cornerstones of teamwork

1. Communication
2. Coordination
3. Collaboration

Research @ NASA Ames

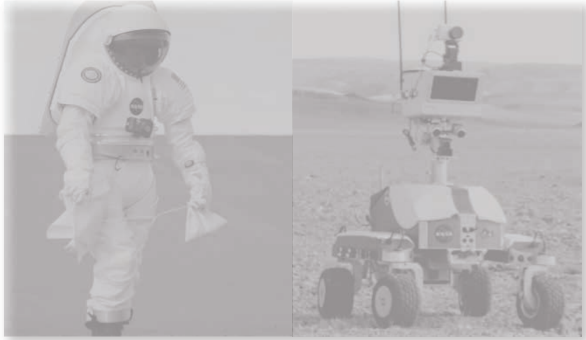
Part 1: Communication

- Signaling for non-humanoid robots
- Convey robot state and intent using dynamic light and sound
- Ambient and active communication



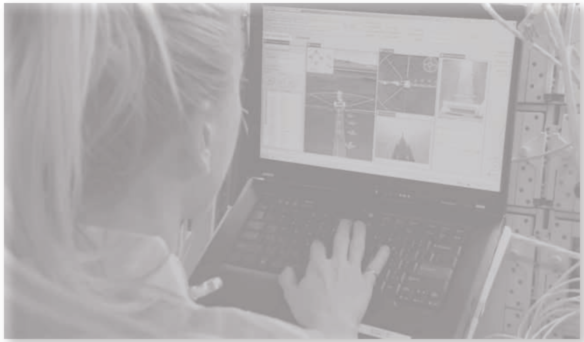
Part 2: Coordination

- Achieve common (joint) objective
- Independent human and robot activities
- Robots work before, in parallel (loosely coupled) and after humans



Part 3: Collaboration

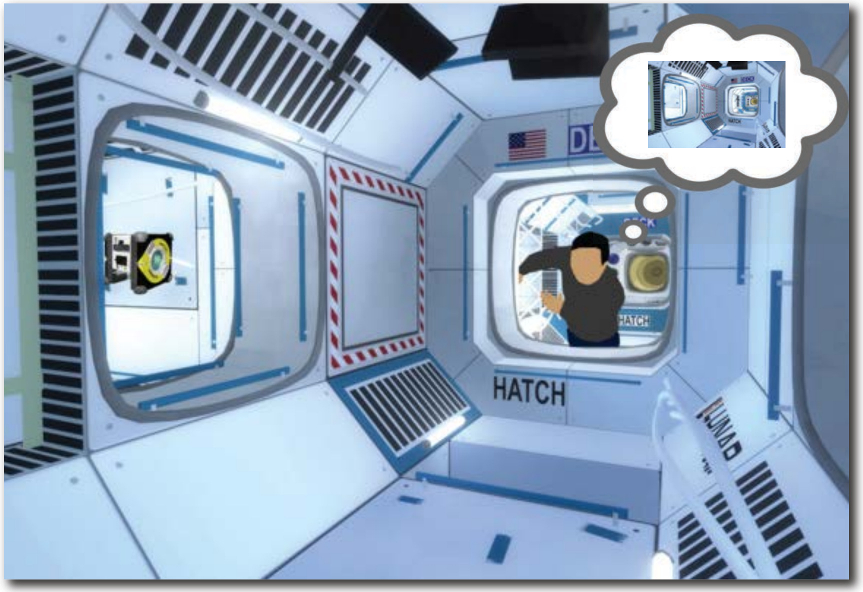
- Humans support autonomous robots
- Focus on cognitive tasks (planning, decision making, etc)
- Human-robot team may be distributed

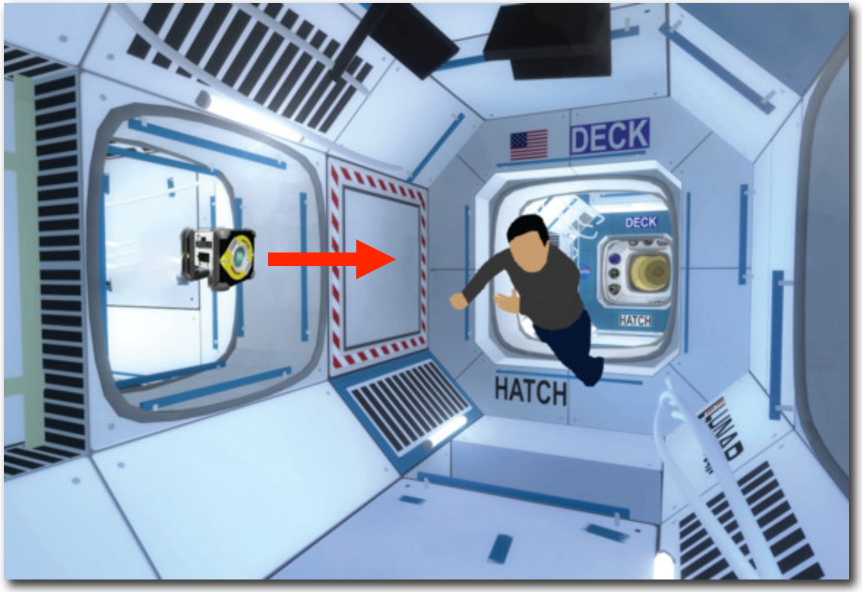


Motivation

Spatial negotiation

- When humans and robots must co-exist in the same space, there is often a need for spatial negotiation
- Cannot always rely on pre-defined rules (e.g., “right of way”) due to ambiguity and uncertainty
- Signaling (lights, movement, sound, etc) is an effective manner to communicate intent and elicit action.

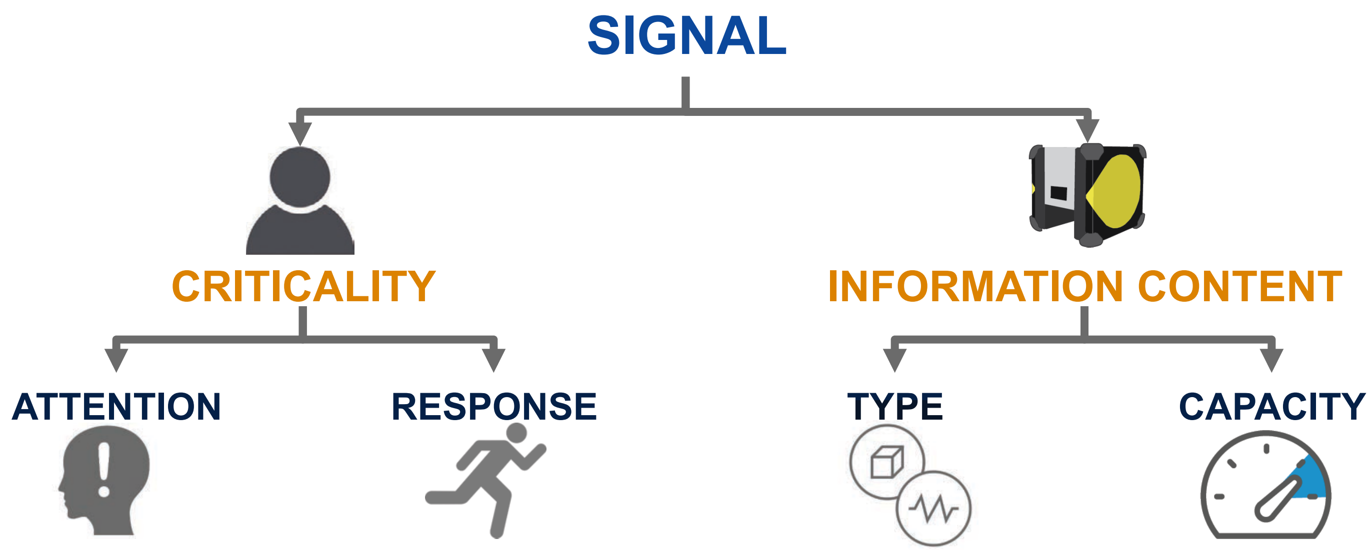




Signaling for human-robot interaction

Considerations

- **What** to convey (importance of the information)
- **When** to convey (timing of the information)
- **How** to convey (constrained/modulated by configuration, situation, etc..)
- **To whom** do we convey (user role, capability to receive/respond, etc.)



E. Cha, Y. Kim, T. Fong, and M. Mataric (2018) **"A survey of non-verbal signal-ing methods for non-humanoid robots"** Foundation & Trends in Robotics 6(4).

Astrobee

Free-flying space robot

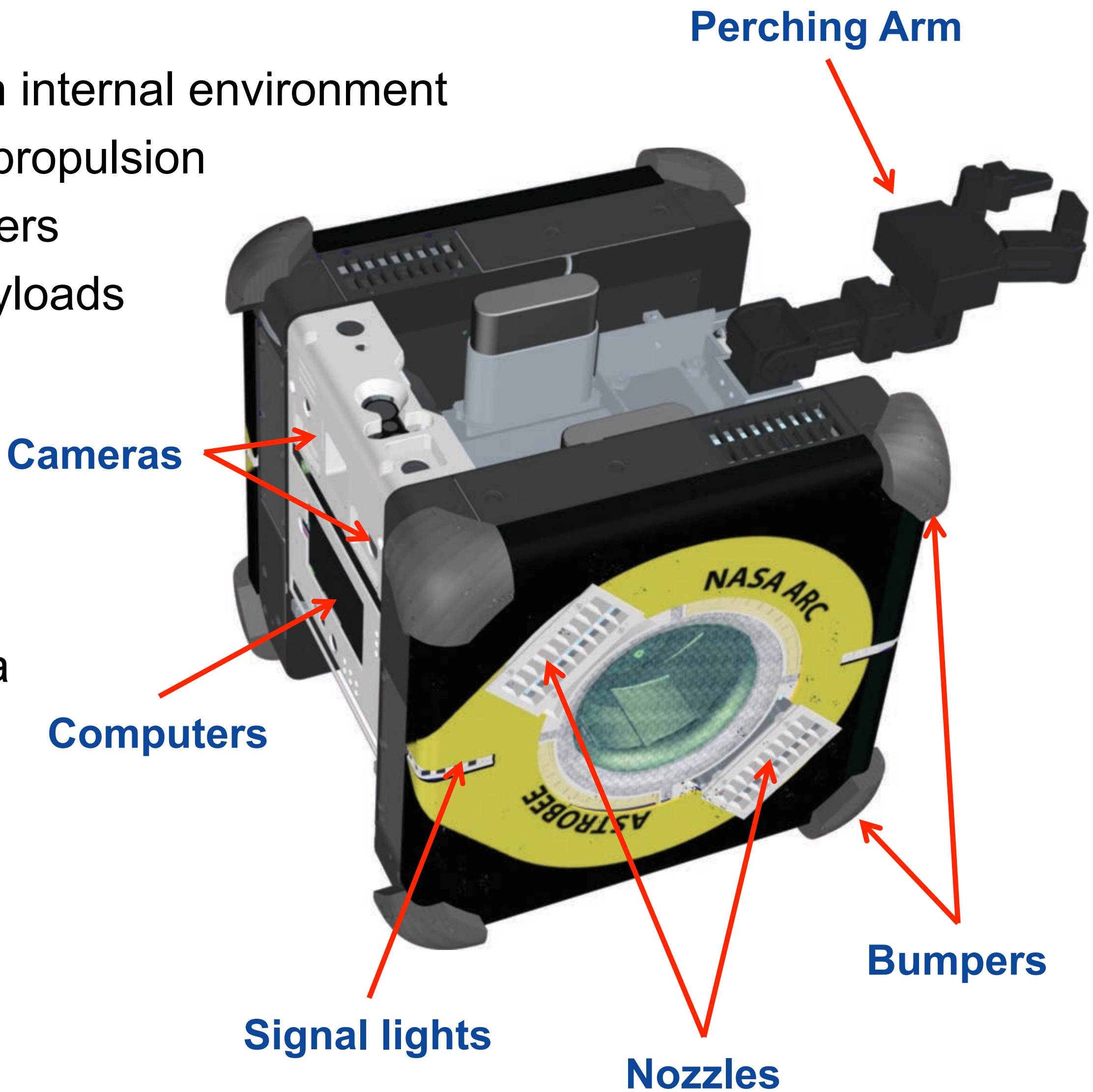
- International Space Station internal environment
- All electric with fan-based propulsion
- Three smartphone computers
- Expansion port for new payloads
- Open-source software
- ~30x30x30 cm, ~8 kg

Uses

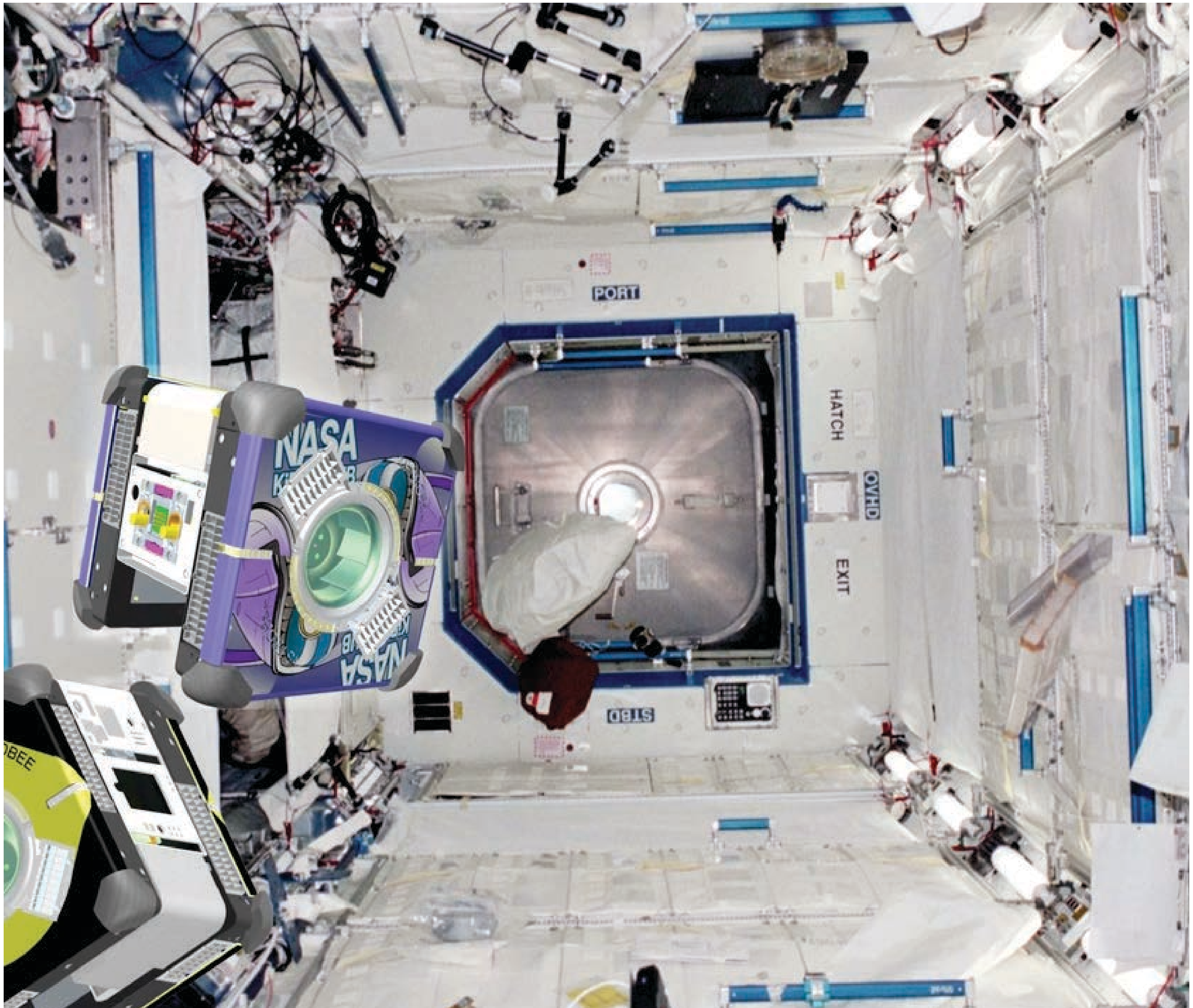
- Mobile sensor
- Remotely operated camera
- Zero-G robotic research

Autonomy

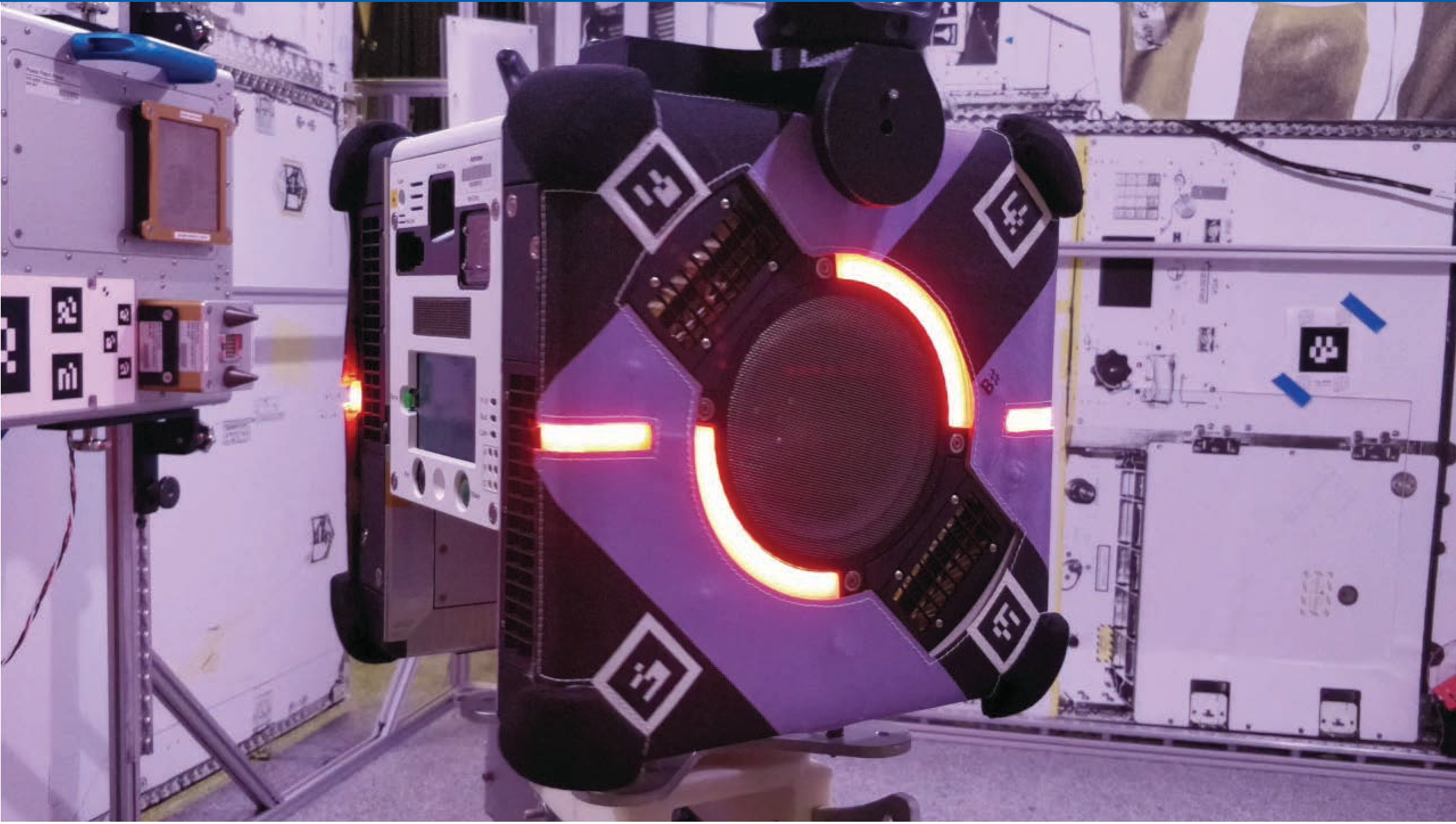
- Docking & recharge
- Perching on handrails
- Vision-based navigation



Astrobee light signal concept



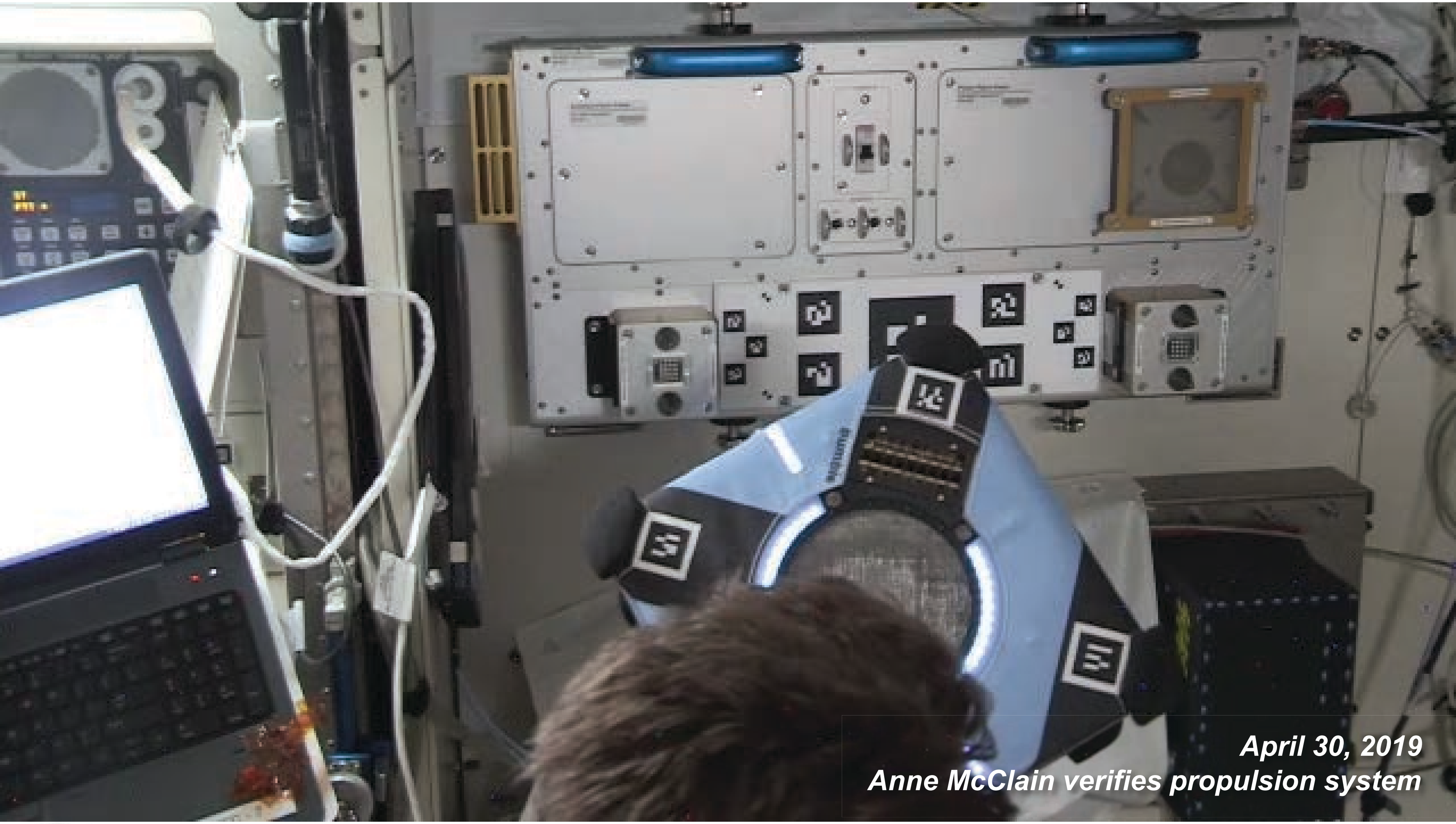
Astrobee development



Astrobee on the Space Station

April 30, 2019
First power-on of “Bumble Bee”

Astrobee on the Space Station



April 30, 2019
Anne McClain verifies propulsion system

Research @ NASA Ames

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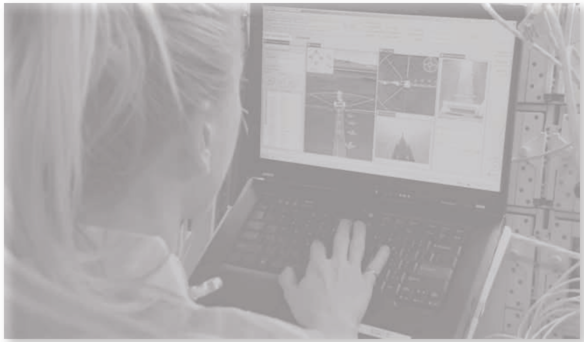


Robots for human exploration

Robots before crew

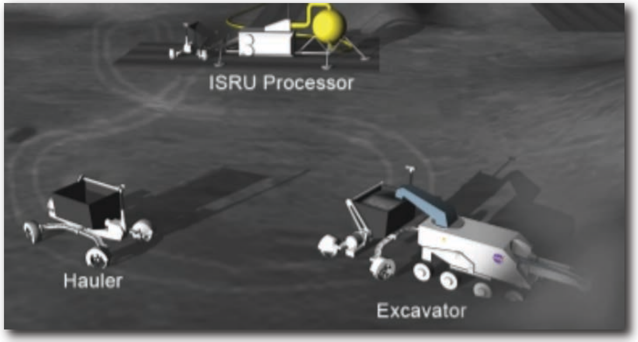
- Prepare for subsequent human mission
- Scouting, prospecting, etc.
- Site preparation, equipment deployment, infrastructure setup, etc.

Robots supporting crew

- Parallel activities and real-time support
- Inspection, mobile camera, etc.
- Heavy transport & mobility

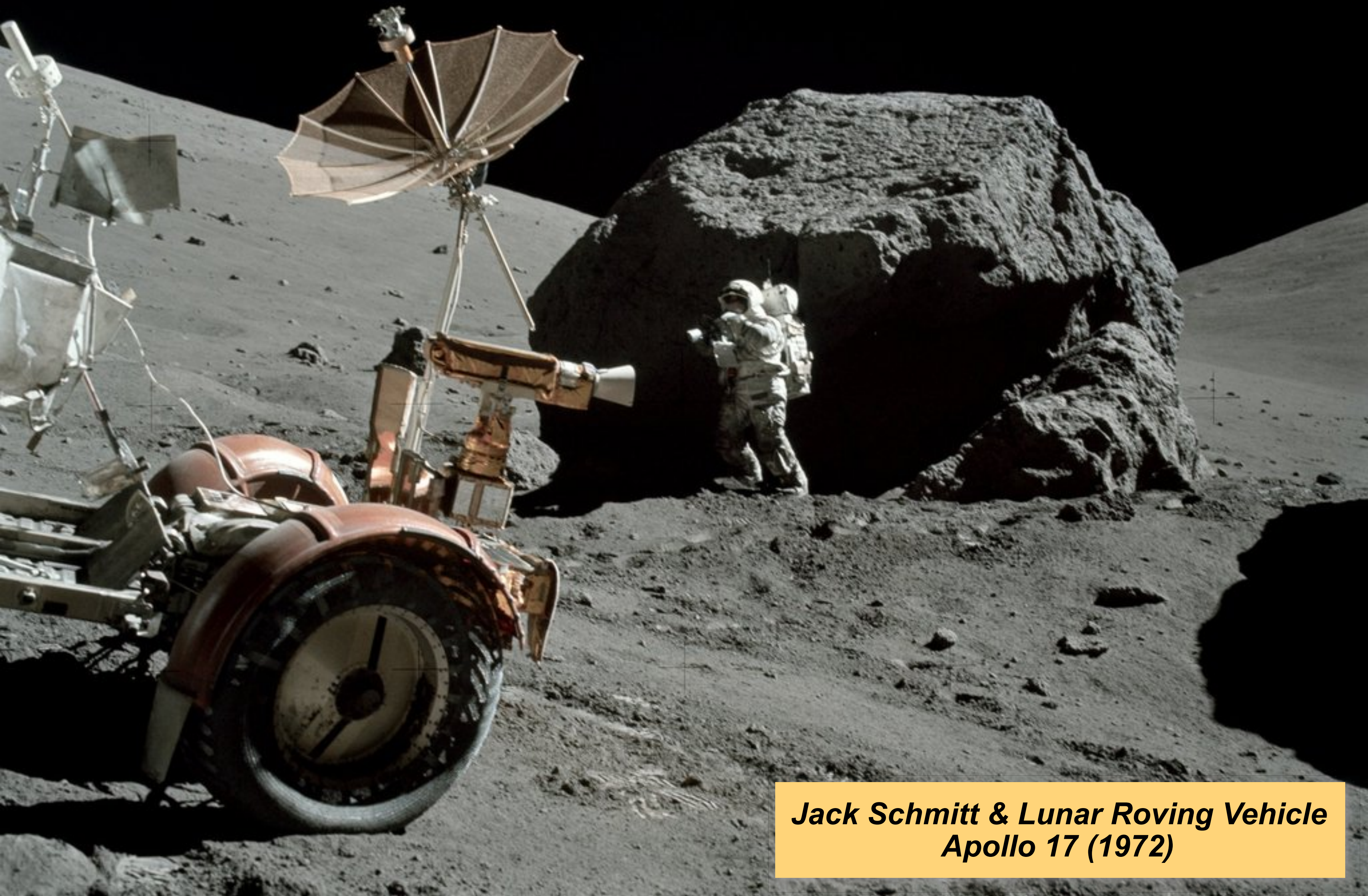
Robots after crew

- Perform work following human mission
- Follow-up and "caretaking" work
- Close-out tasks, maintenance, etc.



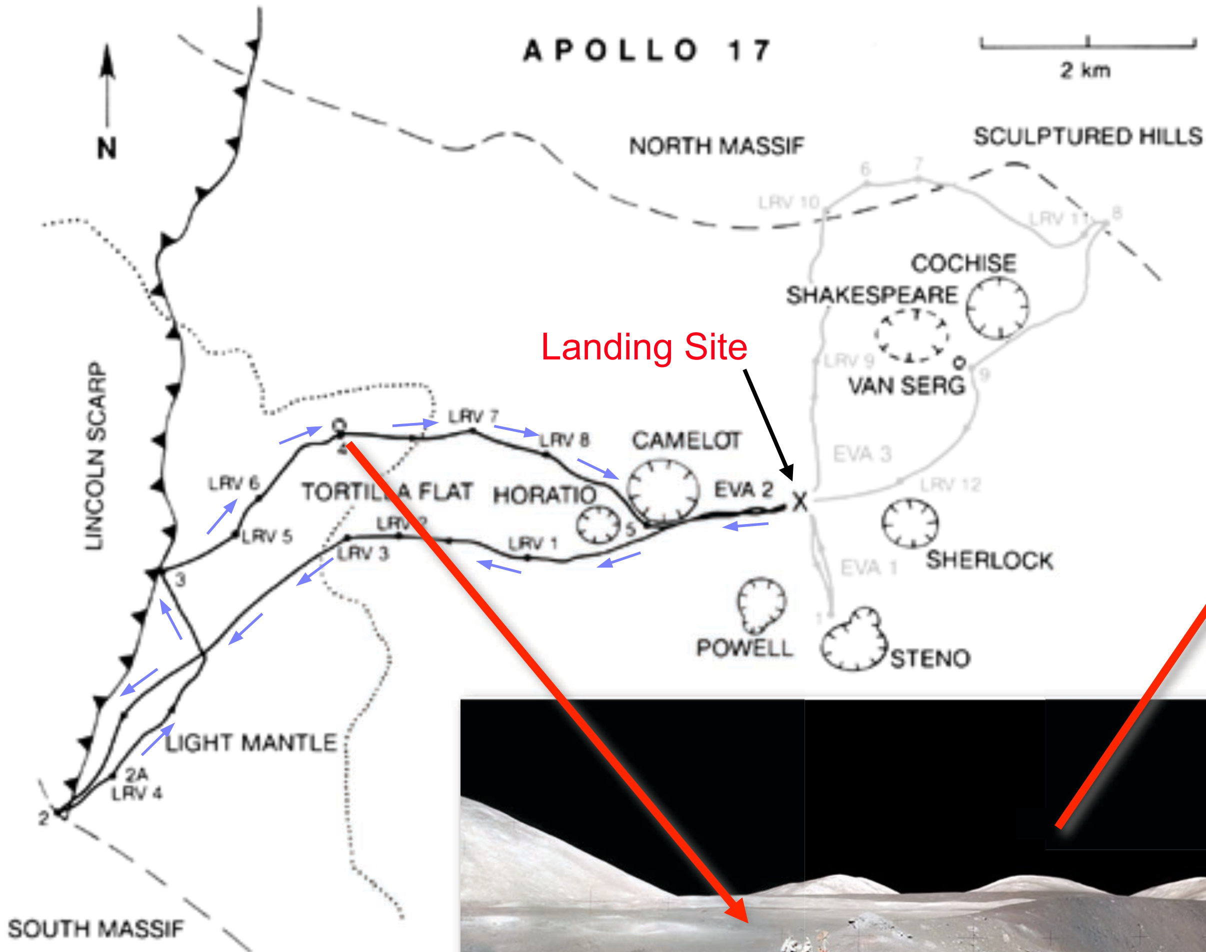
T. Fong, M. Deans, and M. Bualat (2013). **"Robotics for human exploration"**. IFR International Symposium on Robotics

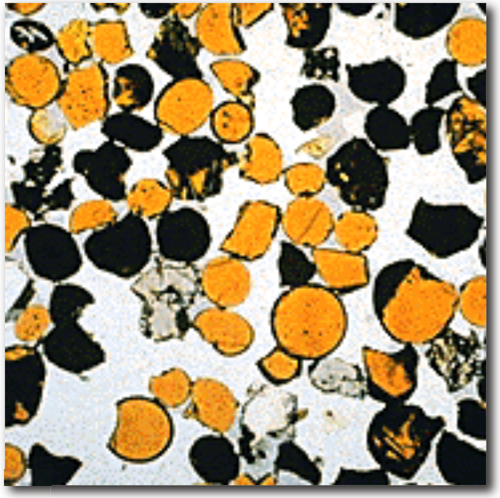
Human planetary exploration

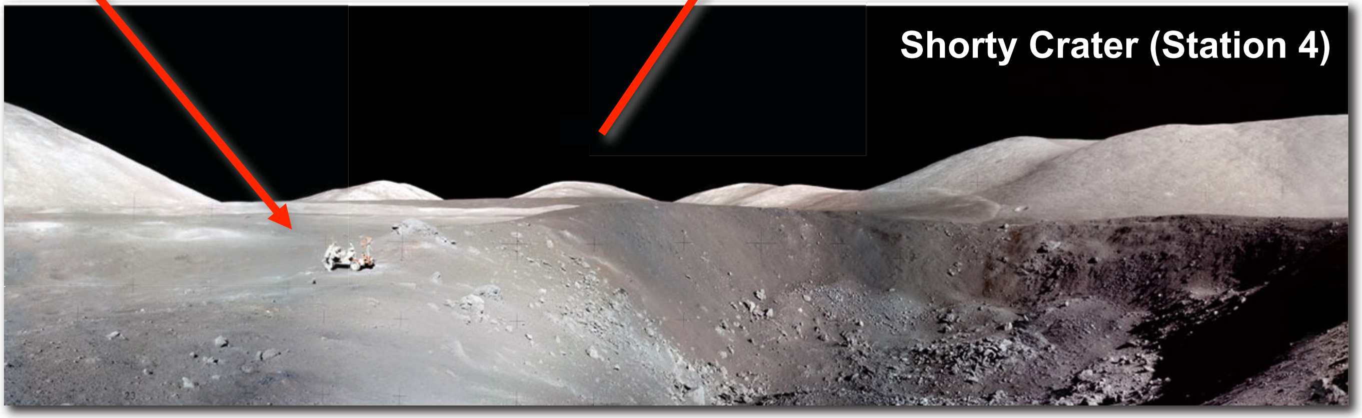


Jack Schmitt & Lunar Roving Vehicle
Apollo 17 (1972)

Why robots should “follow-up” after humans…







Robotic follow-up study

Haughton Crater

- 20 km diameter impact structure
- ~39 million years ago (Late Eocene)
- Devon Island: 66,800 sq. km (largest uninhabited island on Earth)

Crew mission

Mark Helper and Pascal Lee

Essam Heggy and Pascal Lee

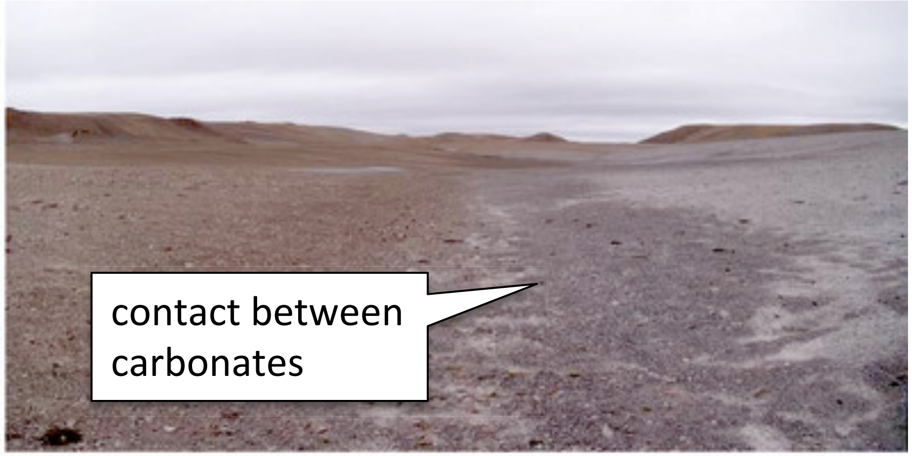
Geologic Mapping

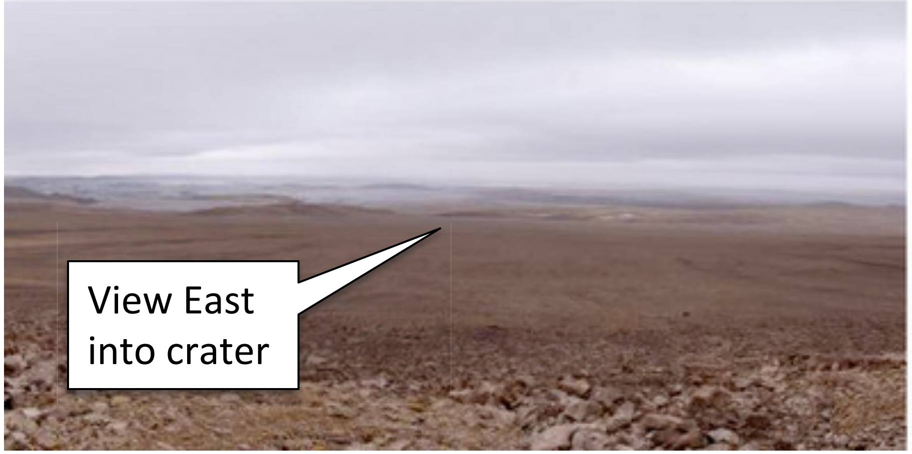
- Document geologic history, structural geometry & major units
- Example impact breccia & clasts
- Take photos & collect samples

Geophysical Survey

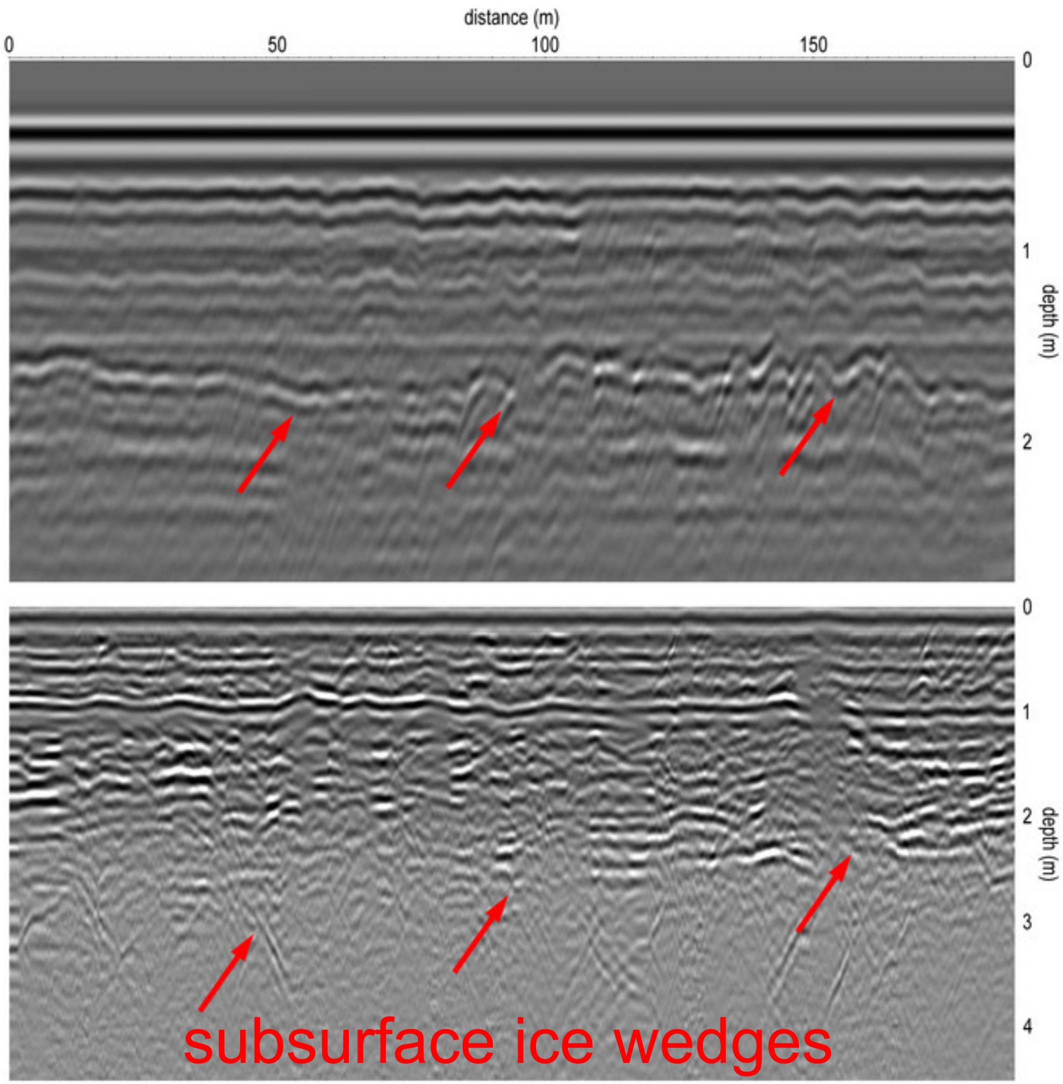
- Examine subsurface structure
- 3D distribution of buried ground ice in permafrost layer
- Ground-penetrating radar: manual deploy, 400/900 MHz

Geologic mapping results

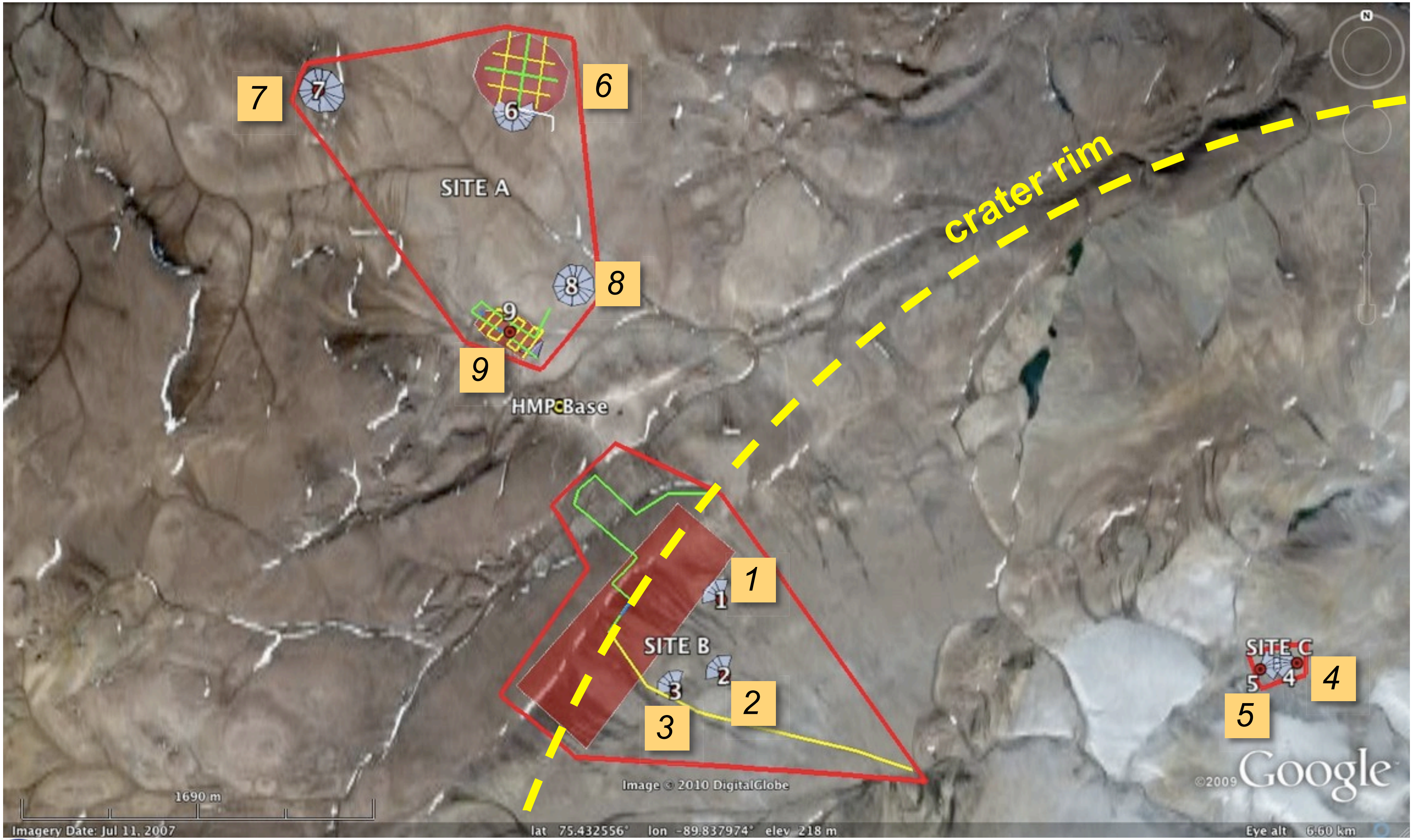




Geophysical survey results



Robotic follow-up plan



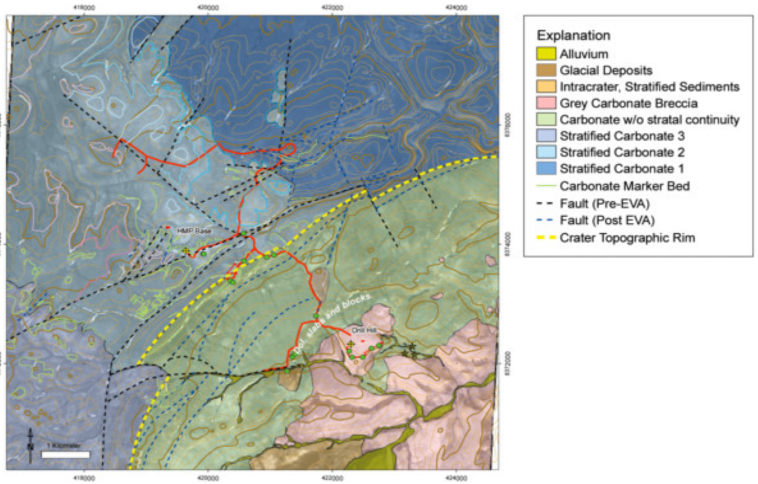
Robotic follow-up results

Geologic Mapping

- **Verified the geologic map** in multiple locations (revisited and confirmed geologic units)
- **Amended the geologic map** in multiple locations (added detail to long-range crew observations)

Geophysical Survey

- **Detail study of "polygons"** (correlated surface & subsurface features identified by crew)
- **Measured average depth** of subsurface ice layer (refined observations from crew)



T. Fong, M. Bualat, et al. (2010) **"Robotic follow-up for human exploration"**. AIAA Space Conf.

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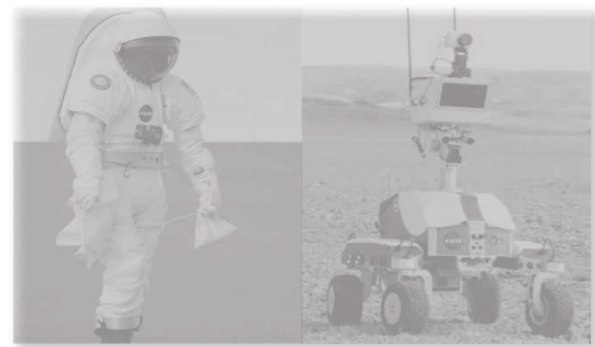

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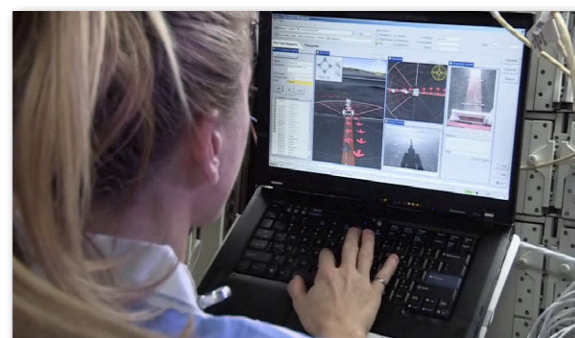


Crew-controlled telerobotics: “Avatar” in real-life

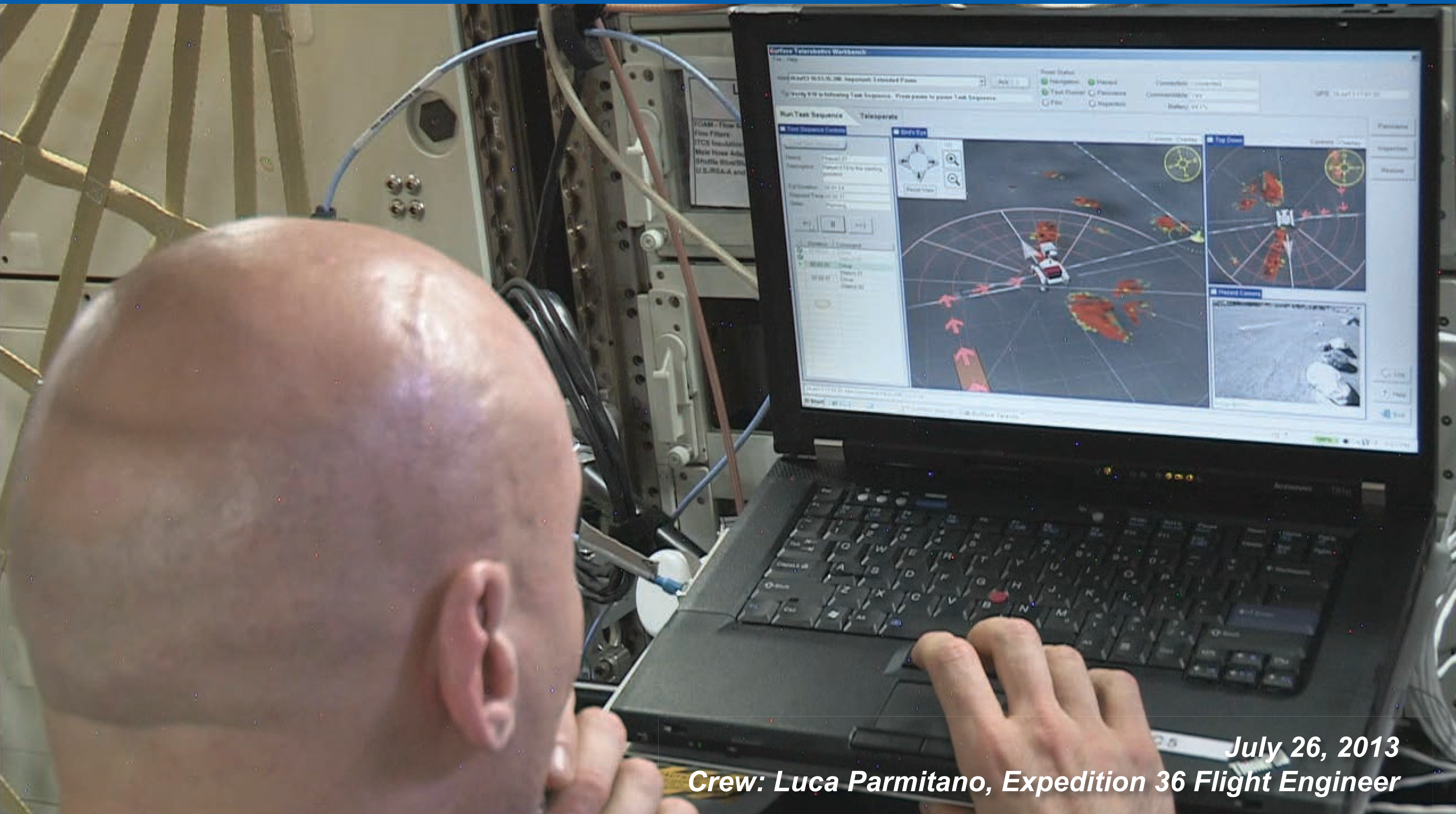
Imperfect robot autonomy

Human-robot collaboration

- Humans provide high-level guidance (not low-level control) to assist when robot **autonomy** is inadequate, untrusted, etc.
- Address the many **anomalies**, **corner cases**, and **edge cases** that require unique solutions, but which are not currently practical to develop, test, and validate under real-world conditions
- Obstacle detection, path planning, sample collection decision making, etc.

Astronaut in space / Robot on Earth

Astronaut remotely helping a space robot



July 26, 2013
Crew: Luca Parmitano, Expedition 36 Flight Engineer

Self-driving cars at NASA Ames

Public/private partnerships

- **Google** (2014-15): collaborative testing of sensors and vehicles
- **Nissan** (2014-19): cooperative software development

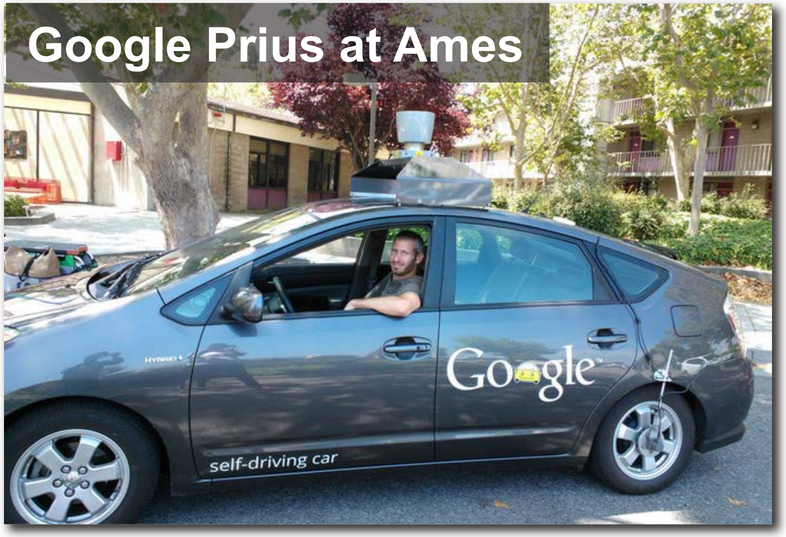
NASA interest

- Expand knowledge of commercial autonomous systems
- Develop protocols and best practices for testing of autonomous systems under **complex real-world conditions**
- Facilitate transfer of NASA technology

Technology maturation

- Safe testing in urban environment
- **Leverage NASA expertise** in autonomy, robotics, safety critical systems, and rigorous testing

Nissan Leaf at Ames

Google Prius at Ames


Imperfect vehicle autonomy

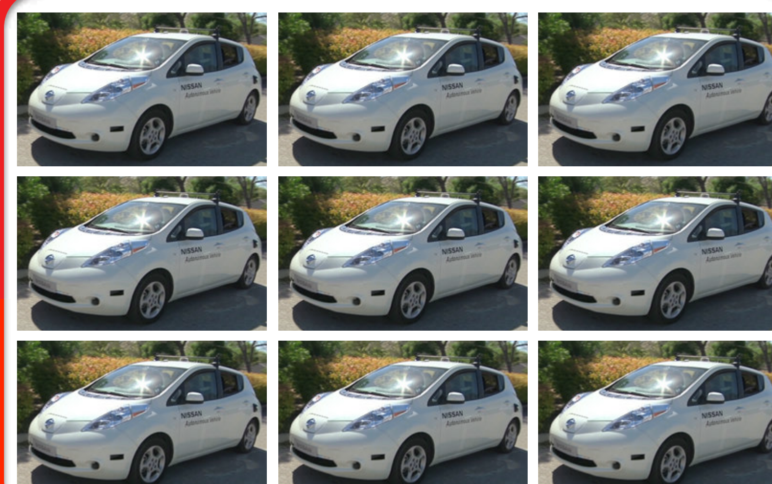
Edge cases, corner cases, and anomalies

- When a construction worker uses hand gestures to provide guidance, or direction, no autonomous car today can reliably make the right decision.
- When the sun is immediately behind a traffic light, most cameras will not be able to recognize the color of the signal through the glare.
- If we see children distracted by the ice cream truck across the street, we know to slow down, as they may dash toward it.

– Andrew Ng (Wired, 3/15/2016)

Support Center / Self-driving car on the road

“Mobility Managers” remotely supporting self-driving cars



CES 2017 demo

Human remotely helping a self-driving car

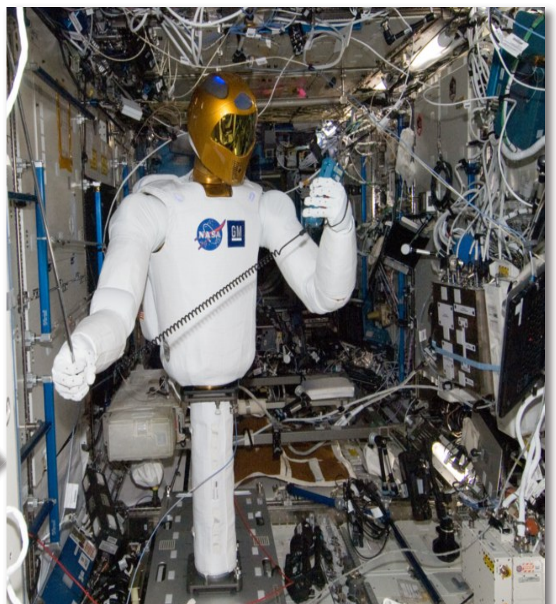
January 6, 2017
Consumer Electronics Show (Las Vegas) & NASA Ames

Teaming with NASA: Small Businesses

SBIR / STTR program **sbir.nasa.gov**

- **Adapt** and **mature** terrestrial robotics technology for space use
- **Identify** and **transition** low-TRL technology from academia
- Build commercial products for **economies of scale** & **sustainability**
- Help NASA move beyond “one-off” components and systems
- **Very important to understand NASA relevance before proposing** !!

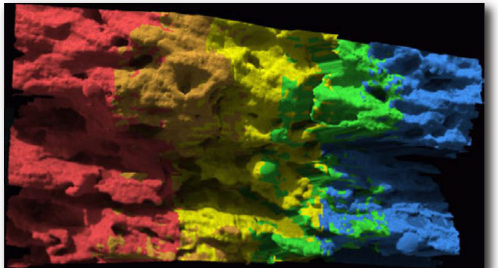
ROS

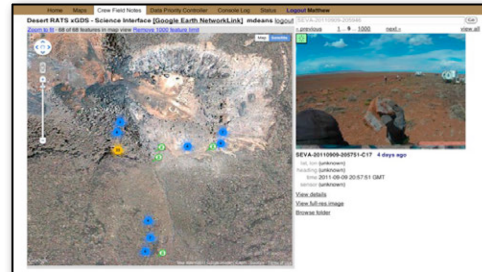


Teaming with NASA: Software Licensing

Vision Workbench

Apache 2



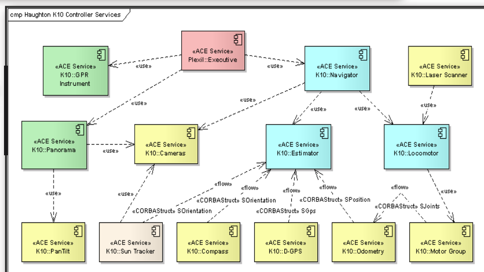


Exploration Ground Data Sys. (xGDS)

Apache 2

RoverSW

NOSA 1.3

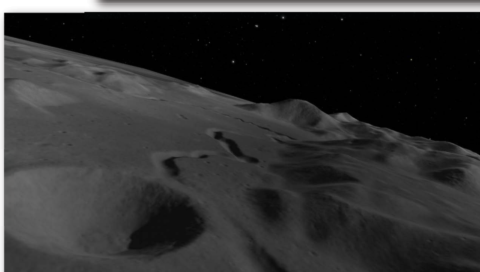


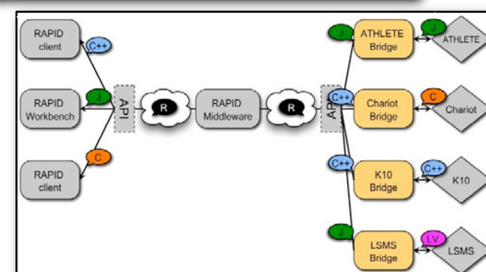
Visual Environment for Remote Virtual Exploration (VERVE)

Apache 2

Neo Geography Toolkit
(Ames Stereo Pipeline)

Apache 2



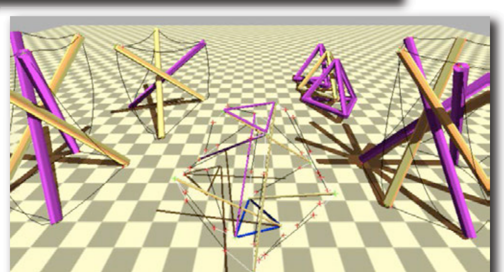


RAPID
(NASA robot middleware)

Apache 2

NASA Tensegrity Robotics Toolkit

Apache 2



Astrobee Robot Software

Apache 2

Teaming with NASA: Partnerships

Academic

- THE ROBOTICS INSTITUTE
- LELAND STANFORD JUNIOR UNIVERSITY — DIE LUFT DER FREIHEIT WEHT — 1891
- VANDERBILT UNIVERSITY
- MIT
- CASE WESTERN RESERVE UNIVERSITY EST. 1826
- Berkeley UNIVERSITY OF CALIFORNIA
- RUTGERS THE STATE UNIVERSITY OF NEW JERSEY
- University of Idaho
- WISCONSIN UNIVERSITY OF WISCONSIN–MADISON
- USC
- BRIGHAM YOUNG UNIVERSITY FOUNDED BYU 1875 PROVO, UTAH
- Cornell University
- UNIVERSITEIT GENT
- SETI INSTITUTE
- KAIST Korea Advanced Institute of Science and Technology 한국과학기술원

Commercial

- Google
- NISSAN
- ASTROBOTIC
- SSL
- ENERGID Robotics and Machine Vision
- Otherlab
- ALTIUS SPACE MACHINES
- PI ProtoInnovations
- TRAC Labs

Government

- DARPA
- MARINE CORPS WARFIGHTING LAB "Semper Fidelis"
- SPAWAR
- NPS PRAESTANTIA PER SCIENTIAM 1909
- NAVAL RESEARCH LABORATORY WASHINGTON, DC
- USGS science for a changing world

Questions?

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Intelligent Systems Division
NASA Ames Research Center

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